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13. ABSTRACT (Maximum 200 words)  This report describes the result from a systematic study on a new device structure, the corrugated quantum well infrared photodetector (C-QWIP), which is designed to couple normal incident radiation into the quantum well structures. The C-QWIP structure is an array of QWIP wires with slant sidewalls, fabricated by etching V-grooves through the detector active region down to the bottom contact. It utilizes total internal reflection at the sidewalls of these QWIP wires to create favorable optical polarization for absorption. We have demonstrated that it has higher coupling efficiency in comparison with the standard 45° edge coupled device. Also, the coupling efficiency is independent of pixel size and wavelength. In addition, due to partial removal of the active material, the dark current of the detector is reduced significantly. The combination of photocurrent increase and dark current decrease results in a larger photocurrent to dark current ratio $r_i$ , and thus a higher $D^*$ and a smaller $NE\Delta T$ in array applications.				
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**Noise Characteristics of Superlattice Energy Filters and Multi-Color Infrared  
Detection Using Quantum Well Microstructure**

**Final Technical Report**

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**This is the final report summarizing the research on quantum well  
detectors for long wavelength imaging applications in the 10  $\mu$ m  
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Despite the fact that high resolution thermal imaging has been demonstrated using quantum well infrared detector (QWIP) technologies, there are still technical problems concerning light coupling in small detector pixels. Conventional light coupling schemes such as diffraction gratings, which rely on collective diffraction effect, or random gratings, which utilize light trapped within device active regions, achieve high quantum efficiencies only when detector sizes are relatively large. In high resolution arrays where pixel areas are limited, these approaches become inadequate. Besides, each set of grating parameters can provide optimal coupling to only one specific wavelength. This wavelength sensitivity limits their utility in broadband or multi-color detection and, at the same time, increases the complexity of array fabrication. In light of these problems, we focus our research on the design, fabrication and testing of QWIP's based on a new light coupling scheme.

This coupling scheme utilizes total internal reflection, instead of diffraction, to change the direction of light for optical absorption. The device structure, which we dubbed the corrugated quantum well infrared photodetector (C-QWIP), consists of an array of triangular prisms created by etching linear V-grooves directly into the active detector region (Fig 1). Normal incident light is reflected by the prism sidewalls and makes four optical passes when the substrate is thinned. With this approach, the light coupling efficiency is expected to be free of detection wavelength dependence and pixel size dependence, two desirable features in multi-color infrared detection and high resolution array applications.

We systematically investigated seven C-QWIP samples with cutoff wavelength  $\lambda_c$  ranging from 5  $\mu\text{m}$  to 17.3  $\mu\text{m}$ . All seven detectors are fabricated using the same mask pattern to test whether a single C-QWIP coupling structure can be universally applied to all detection wavelengths. We also tested the pixel size dependence of the coupling efficiency by fabricating detectors of sizes varying from  $50 \times 50 \mu\text{m}^2$  to  $500 \times 500 \mu\text{m}^2$ .

Fig. 2 shows typical I-V characteristics of a C-QWIP and an edge coupled detector, both from the same wafer with 10.2  $\mu\text{m}$  cutoff wavelength. At the operating temperature of 70 K and an applied voltage of -1.6 V, the dark current density  $J_d$  of the C-QWIP is reduced by a factor of 2.14 compared to that of the edge coupled device (due to partial removal of the active detector region) while the 300 K background photocurrent density  $J_p$  is increased

by a factor of 1.85. The current ratio  $r_I$  of the C-QWIP thus increases by a factor of 4.0, and  $D^*$  by a factor of 2.8.

Fig. 3 shows a typical spectral response of a C-QWIP with  $\lambda_c = 11.2 \mu\text{m}$ , together with that of an edge coupled detector. The C-QWIP has the same peak absorption wavelength and absorption lineshape as that of the intrinsic material. The ability to efficiently couple light through the entire detection window indicates an increase in the overall background photocurrent and therefore, the potential for broadband detection.

Fig. 4 shows the responsivity of four different C-QWIPs with detector linear sizes ranging from  $50 \mu\text{m}$  to  $500 \mu\text{m}$ . No change of the spectral line shape is observed within our experimental error, and the responsivity of the four devices shows no size dependence. The results indicate that the coupling is not a collective effect and does not depend on the number of prisms present in each detector pixel, ideal for high resolution QWIP array applications.

The detectivity of the C-QWIP is also enhanced. Fig. 5 summarizes the ratios of detectivity enhancement  $r_D$ , defined as  $(D^*)_{\text{CQWIP}} / (D^*)_{\text{edge}}$ , along with the current ratio enhancement factors  $F_{\text{imp}}$ , defined as  $(I_p / I_d)_{\text{CQWIP}} / (I_p / I_d)_{\text{edge}}$ , for all seven samples fabricated from the same mask pattern. Although there is some scattering in the experimental data, both  $r_D$  and  $F_{\text{imp}}$  show no trend of increasing or decreasing with  $\lambda_c$  over the entire wavelength range. One may thus conclude that a single C-QWIP design is applicable to detectors with different  $\lambda_c$ . On the average, the detectivity is increased by 2.4 times and the current ratio, by 3.2 times. The fluctuation of the data was attributed to the slight difference in the etching profile of each detector and the insufficient substrate thinning.

In addition to detector sensitivity enhancement, the C-QWIP structure also increases the background limited temperature  $T_{\text{BLIP}}$ , as shown in Fig. 6. In general, the C-QWIP structure increases  $T_{\text{BLIP}}$  by 3 K to 5 K in the entire wavelength range shown. For  $\lambda_c = 9.4 \mu\text{m}$ ,  $T_{\text{BLIP}}$  is 75 K with  $f/1.5$  optics

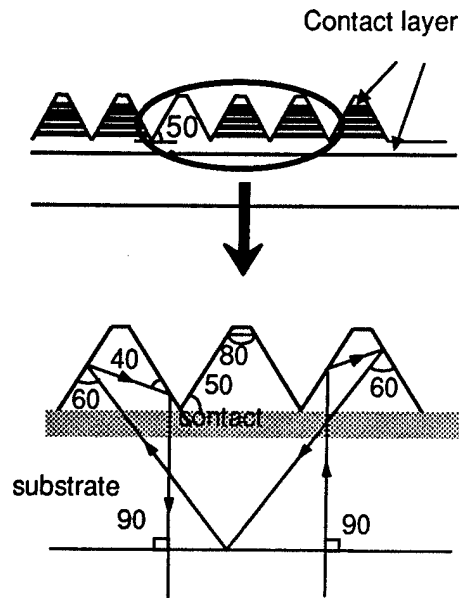


Fig. 1 Ray diagram inside a C-QWIP with 1-D V-groove pattern.

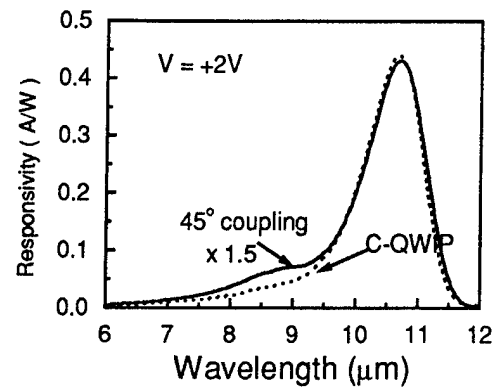


Fig. 3 The spectral response of a C-QWIP (dashed curve) and an edge coupled detector (solid curve), both from the same wafer with  $\lambda_c$  equal to 11.2  $\mu\text{m}$ .

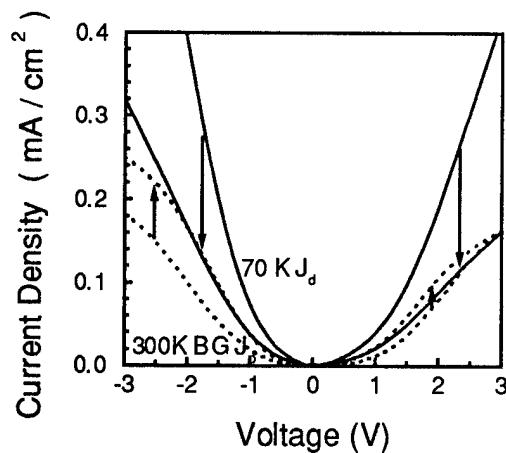


Fig. 2 The reduction of the dark current density  $J_d$  (solid curves) at 70 K and the increase of the background photocurrent density  $J_p$  (dashed curves) for a sample with  $\lambda_c$  equal to 11.2  $\mu\text{m}$ , when the coupling scheme changes from 45° edge coupling to that of the C-QWIP.

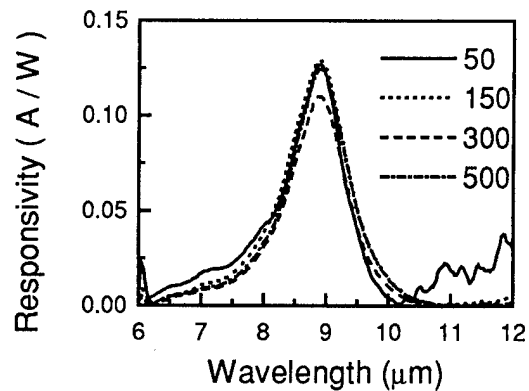


Fig. 4 The responsivity of C-QWIP with different linear sizes: 50  $\mu\text{m}$ , 150  $\mu\text{m}$ , 300  $\mu\text{m}$ , and 500  $\mu\text{m}$ .

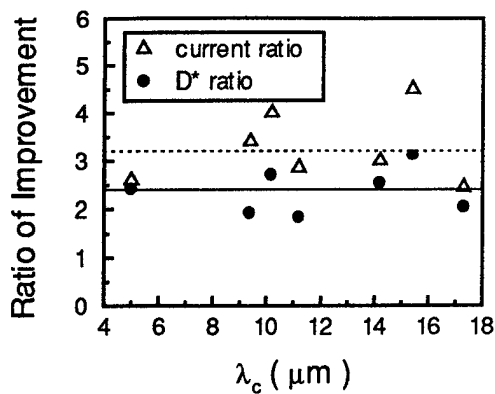


Fig. 5 The detectivity (circles) and current ratio (triangles) enhancements for the C-QWIPs in comparison with the edge coupled detectors. On the average,  $D^*$  is increased by a factor of 2.4 (solid line) and the current ratio is increased by a factor of 3.2 (dot line).

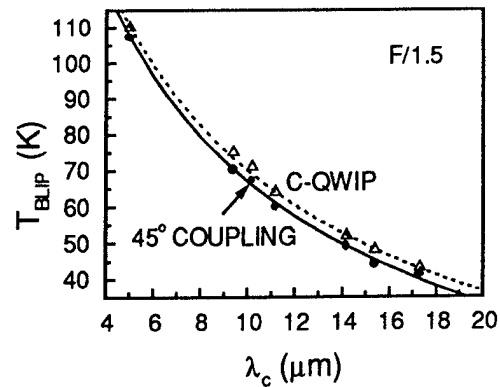


Fig. 6 The background limited temperature for the C-QWIPs (triangles) and the edge coupled detectors (circles) under  $f/1.5$  optics. The curves are guides to the eye only.

## Publications

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4. "Performance of corrugated quantum well infrared photodetector," C.J. Chen, K.K. Choi, W.H. Chang and D.C. Tsui, *Applied Physics Letters* **71**, 3045 (1997).
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